THERMO HYDRAULICS OF A STEAM BOILER FORCED CIRCULATION WITH RIFLED EVAPORATING TUBES

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ABSTRACT:

In order to minimize the dryout at the steam boiler furnace in the Thermal Power Plant Kolubara B, designed are inner rifled wall tubes. This type of tubes, with many spiral grooves cut into the bore, prevents film boiling and enables the nucleate boiling be still maintained under the condition of vapour quality being app. 1.

To verify the choice of the rifled tubes instead of the cheaper, smooth tubes type being justified, analyzed is the change of the actual and critical vapour quality with the furnace height, under uniform and non-uniform heat flux through evaporator walls.

Furthermore, made are hydraulic calculations for various steam boiler loads, in case of both rifled and smooth tubes types, with the purpose to check the rifles influence to pressure drop increase in comparison with the smooth tubes. Also, checked is the selection of the circulation pump.

Key words: evaporator, forced circulation, rifled tubes, critical vapour quality, pressure drop

1. INTRODUCTION

The coal-fired 350 MWe Thermal Power Plant "Kolubara B" is being built by the Electric Power Utility of Serbia [1]. A tower design of the plant steam boiler is applied with an evaporator in a forced circulation loop. The forced flow is provided by circulation pumps added to the circulation loop. The circulation pumps pressure head contributes to the buoyancy forces between the descending subcooled water flow in the downcomer and the ascending two-phase mixture flow in the evaporating tubes and it overcomes the friction and local pressure losses along the circulation loop. Also, rifled tubes with internal helical ribs are applied in the furnace section of the evaporator in order to increase the steam-water mixture turbulization and prevent tubes' wall burnout. The sliding pressure is applied for the boiler load control.

In order to prevent the evaporating tubes burnout, the rifled tubes are applied in the furnace evaporating section. The helical ribs and channels on the inner pipe wall induce the swirl flow and the centrifugal force that separates the liquid phase from the two-phase mixture towards the tube wall. This effect enhances the wall wetting and prevents the critical heat transfer occurrence even under high steam void fraction flow conditions. Hence, compared with the classical tubes with the smooth inner wall, the rifled tubes enable reliable cooling even under lower coolant mass fluxes. The lower coolant circulation rates require less energy consumption for the circulation pumps operation and reduce the plant operational costs. Thermal-hydraulic analyses of the steam generation and working fluid flow in the circulation loop consisting of the drum, downcomer and riser/evaporating tubes should also indicate low load conditions that allow the natural circulation operation, when there is no need for the circulation pumps operation.

In this paper a detailed thermal-hydraulic simulation and analysis of the forced circulation loop of the large steam boiler that is being built in the Thermal Power Plant "Kolubara B" are performed. The rifled tubes in the furnace zone of the evaporating tubes are considered. Calculations are performed for the load range from 40 % to 100 % of the full power. A dependence of all important thermal and hydraulic parameters in the evaporating tubes on the boiler load is predicted, such as working fluid flow rate, steam void fraction, circulation number, circulation velocity, and critical heat flux along the evaporating tubes. In order to demonstrate the influence of the rifled tubes on the increase of the evaporating tubes thermal margin against the burnout and on the circulation loop friction pressure drop, the comparative calculations with the evaporating smooth tubes are performed and compared.

2. THE STEAM BOILER EVAPORATOR AT THE THERMAL POWER PLANT "KOLUBARA B"

The steam boiler at 350 MWe coal fired Thermal Power Plant "Kolubara B" is designed for the lignite with the lower heating value of 6700 kJkg-1. The steam boiler parameters are presented in Table 1 [1].

The steam boiler evaporating tubes are heated by thermal radiation and convection. The evaporating tubes are via a drum, downcomer tubes, circulation pumps, connecting tubes and headers connected into the forced circulation loop. Figure 1 shows the main parts of the circulation loop as follows. Water flows through four downcomer non-heated tubes from the boiler drum (1) to the header (3), and then to the circulation pumps (4). Three circulation pumps are mounted, where two operate and one is auxiliary. The discharge section of the downcomer tubes, from the pumps to the header of the front furnace wall, consists of six tubes (5), where two tubes are connected to each circulation pump. The header of the front furnace wall (6) is connected with the headers of the lateral walls (7), where these are connected via the header of the rear furnace wall (8). The membrane type evaporating tubes (9) are mounted on the furnace walls and in the convective channel. At the top of gas channel they are introduced into the upper headers (10). From each upper header the steam-water mixture flows to the boiler drum through eight connecting tubes (11). The inner side of the furnace wall tubes is rifled, while it is smooth in tubes of the convective channel.

3. HYDRAULIC CALCULATIONS OF THE CIRCULATION LOOP

In order to obtain the absorbed heat loads on corresponding evaporating walls in the boiler furnace and in the convective section, it was first necessary to perform the heat calculation of the steam boiler.

Thermal-hydraulic calculations of the circulation loop are conducted for loads of 100%, 80%, 60% and 40% of the nominal full load. Results of the forced circulation hydraulics are presented in Fig. 2 for both rifled tubes (which corresponds to the boiler design condition) and for the smooth tubes (analyzed comparative design) in the furnace. It is shown that the decrease of the boiler load, and at the same time the decrease of the evaporator operating pressure, leads to the increase of the fluid mass flow rate and the slight increase of the pressure drop in the evaporator.

Figure 3 shows changes of two-phase flow parameters with the boiler load (D). The increase of the mass flow rate (M_{be}), and corresponding mass velocity (m_{oc}), with the boiler load decrease, is the consequence of the higher water density at the lower pressure. The circulation velocity is determined from the mass velocity (w_o=m_{ob}/ρ'), and a slight change of its dependence upon the boiler load is observed. Also, the average values of void fraction in the furnace (φ^{f}_{av}) and convective section (φ^{co}_{av}) of the evaporator show a weak dependence upon the boiler load, which indicates that the sliding pressure dependence on the boiler load change is adequately chosen. The decrease of the steam void fraction at the evaporator outlet with the decrease of the boiler load is caused by two effects. One is the decrease of the heat load, and the other is the thermodynamic effect of the increase of the latent heat of evaporation with a pressure decrease.

It is also interesting to present the calculated dependence of the circulation loop hydraulic characteristics on different boiler loads in the chart with the pump operating characteristic that is provided by the pump manufacturer (Fig. 4). It is shown that the fluid volumetric flow through the evaporator for all boiler loads are very close, and the coefficient of the pump efficiency is nearly maximal in the whole operating range and has a value of 80 %; hence, it can be concluded that the adequate circulation pump is chosen.

The same calculations are performed with smooth furnace tubes in order to compare the evaporator hydraulic characteristics for cases of the rifled and smooth inner surfaces of furnace evaporating tubes. Obtained results are depicted in Fig. 2 with dotted line. The results comparison shows that the pressure drop in case with rifled tubes in the furnace is at maximum 3.7% higher than in case with smooth tubes for the nominal boiler load. At first sight so small difference is not expected, since the increase of the frictional pressure drop in the rifled tube, compared with the smooth tube, is approximately 90% higher in case of two-phase flow with 30% quality and the same other flow parameters [8]. But, observing the whole circulation loop, the length of the rifled tubes is only 25% of the total circulation loop length, and the existence of the thread ribs on the tube inner surface leads to the adjustment of the fluid mass flow rate; for nominal boiler load the flow rate is reduced for 1.7% and for the minimal load 1.1%. Hence, due to the friction pressure drop dependence on the velocity square, and due to the relatively small length of the rifled tubes, the increase of frictional pressure drop in the circulation loop is practically negligible.

4. THE INFLUENCE OF RIFLED TUBES ON THE INCREASE OF THE MARGIN TOWARDS BURN-OUT

Critical steam flow quality is a characteristic of the burnout (or critical heat transfer phenomenon) when the dry-out of the liquid film on the tube wall occurs, while water drops are still present in the steam flow. As stated, the burnout is characterized with the rapid drop of the heat transfer coefficient and tube wall temperature increase. In zones with high temperatures of the combustion products in the furnace, the burnout leads to tube wall thermo-mechanical damage. Hence, a thermal-hydraulic design of the steam boiler must provide that flow quality values along the evaporator are lower than critical ones.

In order to increase the margin towards the burnout occurrence, the rifled tubes with the thread ribs on the inner side are applied in the design of the steam boiler of the TPP "Kolubara B". The advantage of the rifled tubes is more pronounced in case of higher pressures and higher heat loads.

Figure 5 shows the change of the flow quality and its critical value along the evaporator height under the forced circulation and uniform heat load among evaporator walls. It is shown that the quality does not exceed the critical values, whereas the margin towards the critical values is much higher in the rifled than in smooth tubes.

Presented results are obtained under the uniform heat load distribution among the evaporator walls. In real operating conditions the non-uniformity of the furnace heat loads exists and it is more or less exaggerated. The non-uniformity of the heat load exists due to some burners malfunction or switch off, or because of a different fouling of the walls. Because of that some tubes or all tubes at some furnace wall receive a different heat load in real operating conditions than the average value determined by the boiler heat calculation.

In order to get an insight into the influence of the heat load non-uniformity on the thermal-hydraulic parameters of the steam and water two-phase flow, the thermal-hydraulic calculation is performed under the assumption that the front wall receives 70% lower heat load than average, the rear wall receives 70% higher heat load, and the loads of the lateral walls are symmetrical and equal to the average load. The change of the flow quality along the evaporator height is shown in Fig. 6 for both rifled and smooth tubes in the evaporating tubes of the furnace section.

Also, the heat fluxes and mass velocities in the furnace walls are shown. The greatest quality occurs in the rear wall since it absorbs the greatest heat load.

The application of the rifled tubes provides the satisfactory protection against the burnout for the evaporator section in the furnace (Fig. 6a). In the rear evaporator wall in the convective gas channel the quality exceeds its critical value. But, in that section the heat flux has a low value and the tubes burnout could not occur.

In case of the smooth tubes application in the furnace section, the critical steam quality is achieved in zones of high temperatures, which would lead to tubes burnout. Hence, this analysis shows the necessity of the application of the rifled tubes in the furnace section of the evaporator in order to provide evaporators safety against the burnout.

5. CONCLUSIONS

1. According to the simulation results in Fig. 2, the circulation velocity and steam void fraction practically do not change with the boiler load, which confirms that the sliding pressure dependence on the boiler load is adequately defined.

2. The calculated hydraulic characteristics of both forced and natural circulation loops with rifled and smooth tubes in the evaporating tubes in the furnace section are analyzed. The results show that in case of the smooth tubes the circulation mass flow rate is increased for only 1.7% under the 100% load and 1.1% under the 40% load compared to the case with rifled tubes. Hence, it can be concluded that the rifled tubes practically do not influence the evaporator's hydraulic characteristics and they do not increase the energy consumption of the circulation pumps.

3. The conducted analyses show that the rifled tubes prevent the critical heat transfer conditions in the furnace zone under all operating conditions and under supposed non-uniform heat load distribution among the evaporator's walls. In case of non-uniform heat load the critical heat flux can be reached in the convective zone of the most loaded evaporating tubes. But, in this zone the heat fluxes are lower compared to the furnace zone and they can not lead to the tubes burnout.

4. In case of the smooth tubes application in the evaporator furnace zone, Fig. 6b shows that the critical heat transfer conditions can be reached in the furnace zone under non-uniform heat load distribution among the evaporating walls. This fact justifies the need for the rifled tubes implementation in the furnace zone of the evaporator.

References

[1] The contract for the delivery of equipment and services for the steam boiler plant at the Thermal Power Plant "Kolubara B", Technical specification, The Electric Power Utility of Serbia - Thermal Power Plant "Kolubara B", Combustion Engineering - Supperheater Ltd., Belgrade, 1986.

[2] E.J. Adam, J.L. Marchetti, Dynamic simulation of large boilers with natural recirculation, Computers & Chemical Engineering, 23 (1999) 1031-1040.

[3] H. Kim, S. Choi, A model on water level dynamics in natural circulation drum-type boilers, International Communications in Heat and Mass Transfer, 32

(2005) 786-796.

[4] O.M. Baldina, V.A. Lokschin, D.F. Peterson, I.E. Semenovker, A.L. Schvarc, Hydraulic calculation of boiler plants - The Normative method, Energia, Moscow, 1978. (in Russian)

[5] J.M. Delhaye, M. Giot, M.L. Riethmuller, Thermohydraulics of Two-Phase Systems for Industrial Design and Nuclear Engineering, Hemisphere, Washington, 1981.

[6] V. Stevanovic, M. Studovic, A Simple Model for Vertical Annular and Horizontal Stratified Two-Phase Flows with Liquid Entrainment and Phase Transitions - One-Dimensional Steady-State Conditions, Nuclear Engineering and Design, Vol.154 (1995) pp.357-379.

[7] Z. Stosic, V. Stevanovic, Numerical Prediction of Pipe CHF Data with Multi-Fluid Modelling Approach, Proceedings of the Eleventh International Conference on Nuclear Engineering - ICONE 11, Tokyo, Japan, April 20-23, 2003, paper ICONE11-36382.

[8] W. Kastner, V. Kefer, W. Koehler, W. Kraetzer, Heat transfer and pressure loss in tubes heated from one side, as well as in inclined and rifled tubes, (Warmeubergang und Druckverlust in einseiting beheizten, geneigten und innen-berippten Rohren), Siemens Aktiengesellschaft Unternehmensbereich KWU, Erlangen, 1988. (in Geraman)

[9] W. Kastner, W. Koehler, W. Kraetzer, Post-Dryout heat transfer in uniformly heated vertical and horizontal tubes, (Warmeubergang im Post-Dryout-Bereich an vertikalen und horizontalen Rohren bei gleichformiger Beheizung), Final report of BMFT Project, 03E-1409-A, Siemens Aktiengesellschaft Unternehmensbereich KWU, Erlangen, 1982. (in Geraman)

[10] P.B. Whalley, Two-Phase Flow and Heat Transfer, Oxford University Press, Oxford, 1986.

[11] Combustion Engineering - Canada P.O. 29647, Boiler circulating pumps, Thermal Power Plant "Kolubara B" - Unit 1, Contract No. CA86104.

[12] D. Tucakovic, Influence of variable operating conditions of the steam boiler with forced circulation on thermal-hydraulic parameters in the evaporator, PhD Thesis, Faculty of Mechanical Engineering, University of Belgrade, Belgrade, 2003.

Table 1: Design parameters of the steam boiler at the Thermal Power Plant "Kolubara B"

Live steam generation,	$D = 292$ kg/s
Live steam pressure,	$p_s = 18.0$ MPa
Live steam temperature,	$t_s = 540$ °C
Reheated steam mass flow rate,	$D_r = 269$kgs^{-1}
Reheated steam pressure,	$p_{rs} = 4.0$ MPa
Reheated steam temperature,	$t_{rs} = 540$ °C
Steam pressure at the reheater inlet,	$p_r = 4.2$ MPa
Steam temperature at the reheater inlet,	$t_r = 330$ °C
Feedwater temperature,	$t_{fw} = 250$ °C

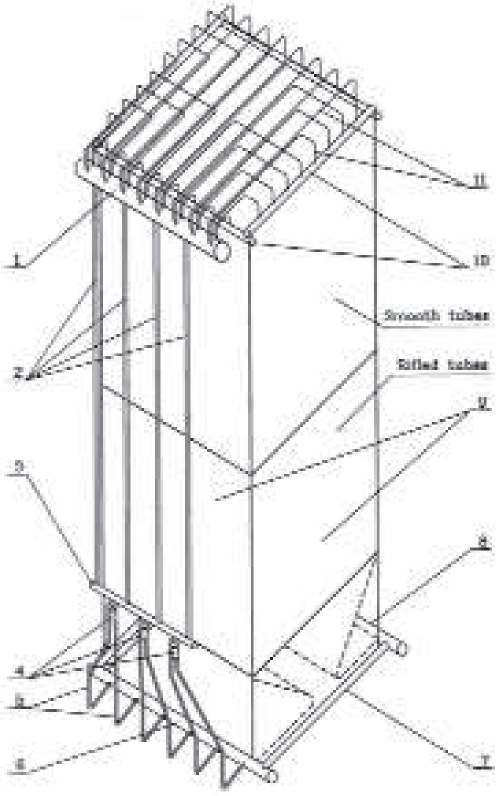

Figure 1. Scheme of the steam boiler evaporator

1. Boiler drum; 2. Downcomer tubes (suction section); 3. Header; 4. Circulation pumps; 5. Downcomer tubes (discharge section); 6. Header of the furnace front wall; 7. Header of the furnace lateral wall; 8. Header of the furnace rear wall; 9. Evaporating tubes; 10. Upper headers; 11. Connecting tubes.

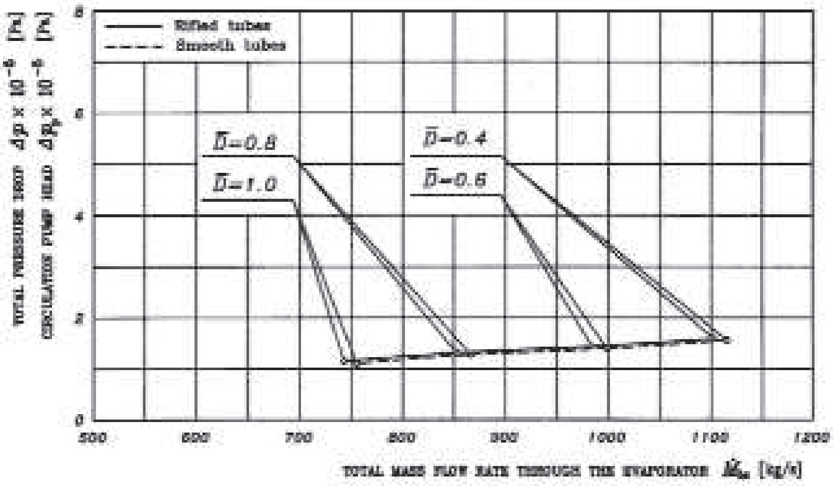

Figure 2. ***Hydraulic characteristic of the evaporator with the forced circulation in cases of rifled and smooth tubes.***

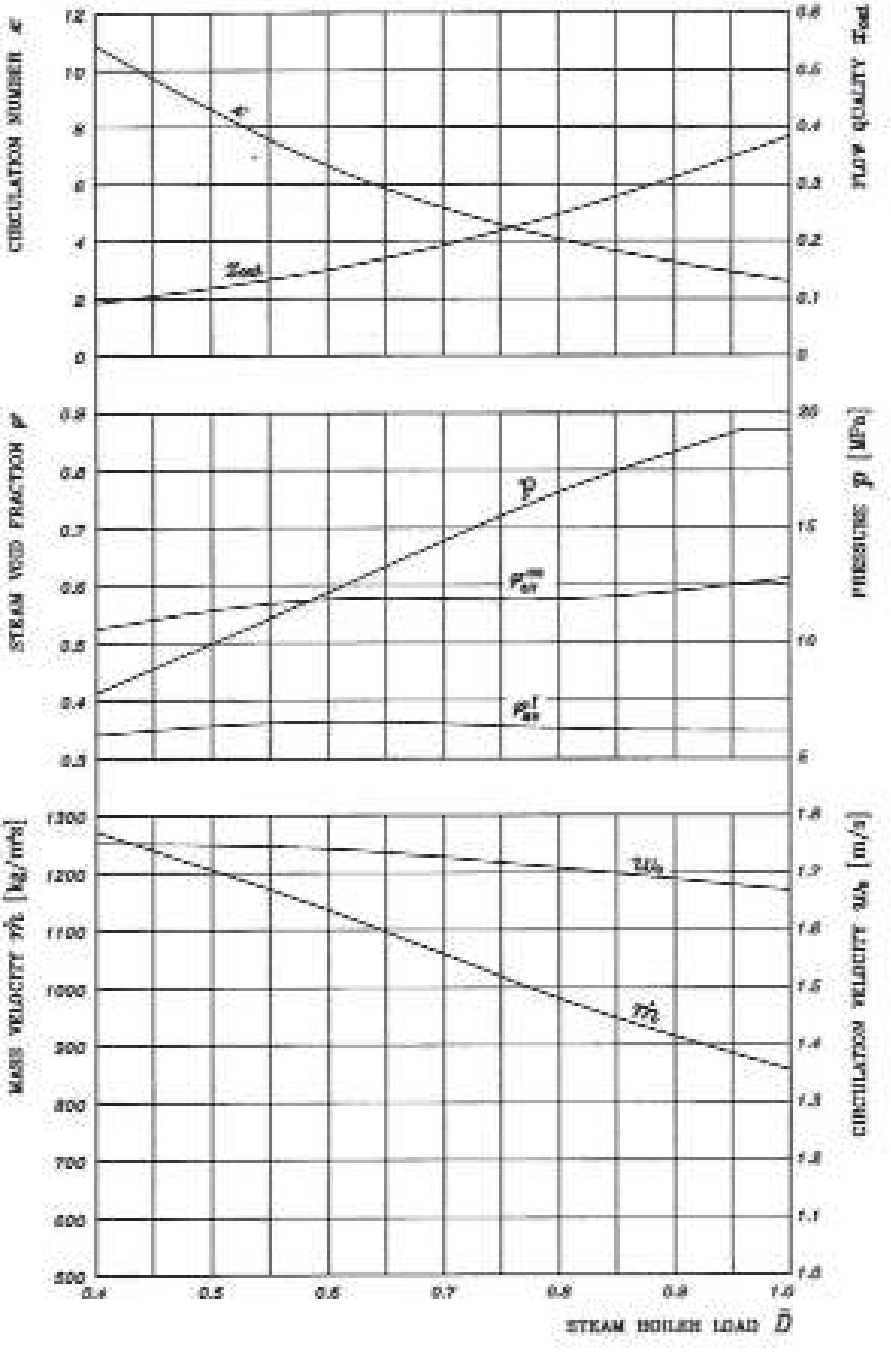

Figure 3. ***Calculated thermal-hydraulic parameters for the evaporator forced circulation.***

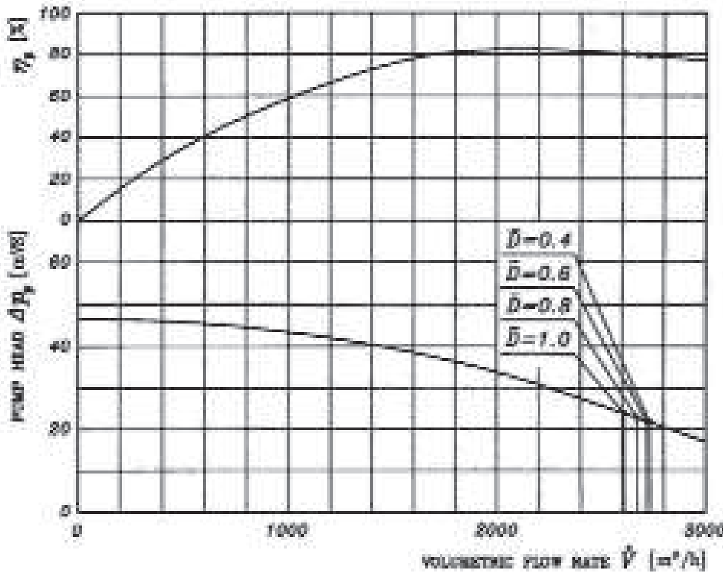

Figure 4. ***Evaporator operating points dependence on the boiler load***

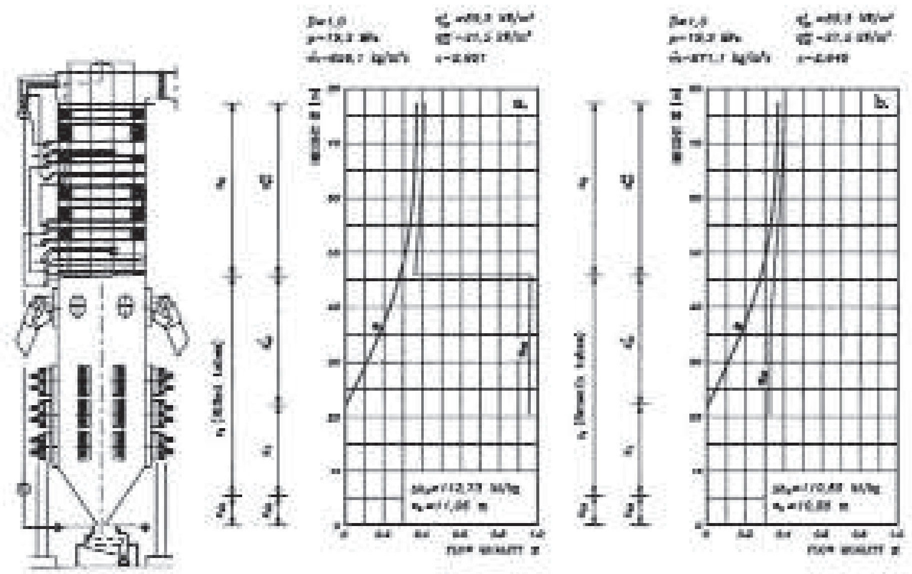

Figure 5. ***Change of the flow quality along the evaporator height under the forced circulation and uniform heat load among the evaporator walls à) Rifled tubes in the evaporator; b) Smooth tubes in the evaporator***

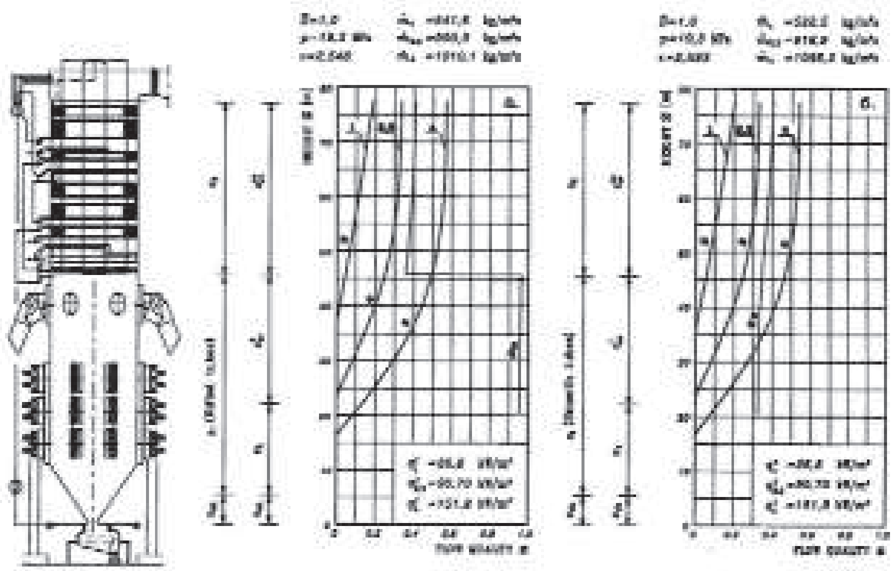

Figure 6. *Change of the flow quality along the evaporator height under the forced circulation and non-uniform heat load among the evaporator walls*
à) Rifled tubes in the evaporator; b) Smooth tubes in the evaporator (1-front wall, 2,3-lateral walls, 4-rear wall)

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